Accounting for Correlated Satellite Observation Error in NAVGEM

Bill Campbell and Liz Satterfield

Naval Research Laboratory, Monterey CA

Presented at the AMS Annual Meeting

4-8 January 2015

Phoenix, AZ

Sources of Observation Error

1) Instrument error (usually, but not always, uncorrelated)
2) Mapping operator (**H**) error (interpolation, radiative transfer)
3) Pre-processing, quality control, and bias correction errors
4) Error of representation (sampling or scaling error), which can lead to correlated error:

True Temperature in Model Space

Subgrid Scale Temperature

T=28°	T=38°	T=58°
T=30°	T=44°	T=61°
T=32°	T=53°	T=63°

Current State of the Art

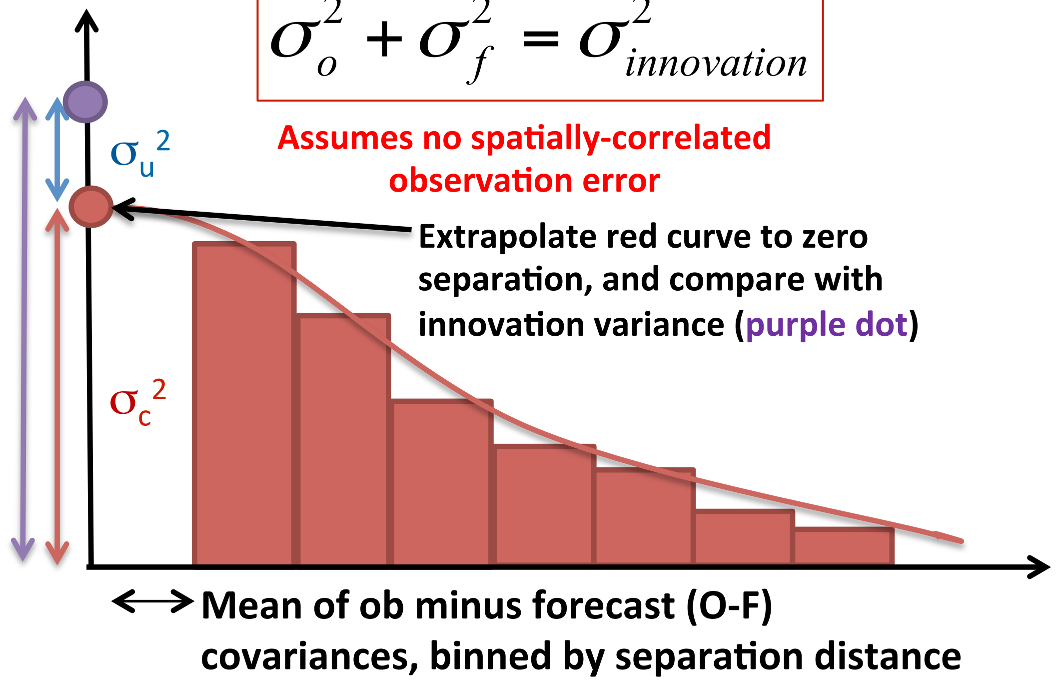
- **Most* current DA methods generally assume no correlations between observations at different levels or locations (i.e., a diagonal R)**
- **To compensate for observation errors that *are* actually correlated, one or more of the following is typically done:**
  - **Discard ("thin") observations until the remaining ones are uncorrelated (Bergman and Bonner (1976), Liu and Rabier (2003))**
  - **Local averaging ("superobbing") (Berger and Forsythe (2004))**
  - **Inflate the observation error variances (… 08, 2013)**
- **Recent theoretical studies (e.g. Stewart et a … that including even *approximate* correlation stru … ms diagonal R with variance inflation**

- ***In January, 2013, the Met Office went operational with a vertical observation error covariance submatrix for the IASI instrument, which showed forecast benefit in seasonal testing in both hemispheres (Weston et al. (2014))**

Hollingsworth-Lönnberg Method

(Hollingsworth and Lönnberg, 1986)

$$\sigma_o^2 + \sigma_f^2 = \sigma_{innovation}^2$$



- Use innovation statistics from a dense observing network
- Assume horizontally uncorrelated observation errors
- Calculate a histogram of background innovation covariances binned by horizontal separation
- Fit an isotropic correlation model, extrapolate to zero separation to estimate the correlated (forecast) and uncorrelated (observation) error partition

Desroziers Method

(Desroziers *et al.* 2005)

- From O-F, O-A, and A-F statistics, the observation error covariance matrix **R**, the representer HBH^T, and their sum can be diagnosed
- This method is sensitive to the **R** and HBH^T that is prescribed in the DA system
- An iterative approach may be necessary

$$E\left[\mathbf{d}_A^O\left(\mathbf{d}_F^O\right)^T\right]=\mathbf{R}$$

$$E\left[\mathbf{d}_F^A\left(\mathbf{d}_F^O\right)^T\right]=\mathbf{HBH}^T$$

$$E\left[\mathbf{d}_F^O\left(\mathbf{d}_F^O\right)^T\right]=\mathbf{R}+\mathbf{HBH}^T$$

4DVar Primal Formulation

$$\underline{w} \equiv \underline{x} - \underline{x_f} = BH^T\left(HBH^T + R\right)^{-1}\left(\underline{y} - H\underline{x_f}\right)$$

$$\left(B^{-1} + H^T R^{-1} H\right)\underline{w} = \left(B^{-1} + H^T R^{-1} H\right)BH^T\left(HBH^T + R\right)^{-1}\left(\underline{y} - H\underline{x_f}\right)$$

$$\left(B^{-1} + H^T R^{-1} H\right)\underline{w} = H^T R^{-1}\left(\underline{y} - H\underline{x_f}\right)$$

$$\underline{s} \equiv B^{1/2}\underline{w}$$

Scale by $B^{-1/2}$

$$\underline{w} = B^{-1/2}\underline{s}$$

$$B^{-1/2}\left(B^{-1} + H^T R^{-1} H\right)\left(B^{-1/2}\underline{s}\right) = B^{-1/2} H^T R^{-1}\left(\underline{y} - H\underline{x_f}\right)$$

$$\left(I + B^{-1/2} H^T R^{-1} H\right)B^{-1/2}\underline{s} = B^{-1/2} H^T R^{-1}\left(\underline{y} - H\underline{x_f}\right)$$

4D-var iteration is on this problem -- We need to invert R!

4DVar Dual Formulation

- An advantage of the dual formulation is that correlated observation error can be implemented directly
- No matrix inverse is required, which lifts some restrictions on the feasible size of a non-diagonal R
- In particular, implementing horizontally correlated observation error is significantly less challenging

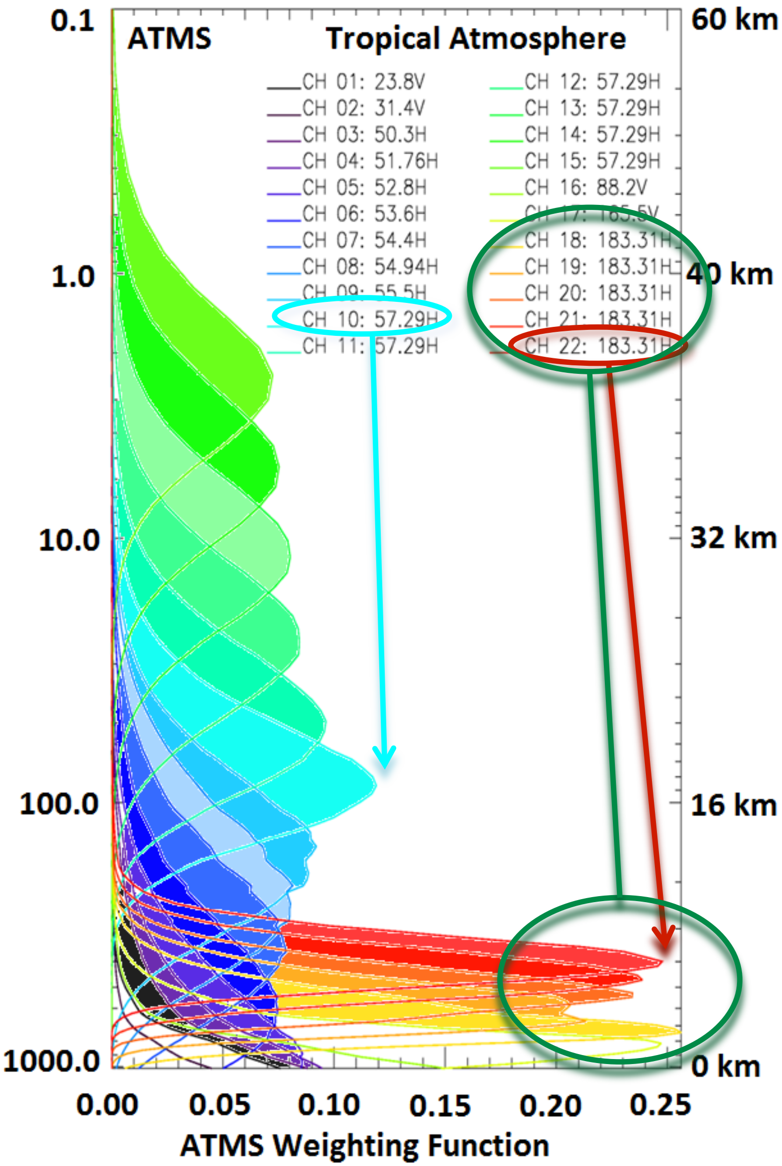
$$\tilde{R}^{-1/2}(HBH^{T}+\tilde{R})\tilde{R}^{-1/2}\left(\tilde{R}^{1/2}\underline{z}\right)=\tilde{R}^{-1/2}(\underline{y}-H\underline{x}_{b})$$

$$(\tilde{R}^{-1/2}HBH^{T}\tilde{R}^{-1/2}+I)\underline{w}=\tilde{R}^{-1/2}(\underline{y}-H\underline{x}_{b})$$

C

4D-Var iteration is on this problem – No need to invert C!

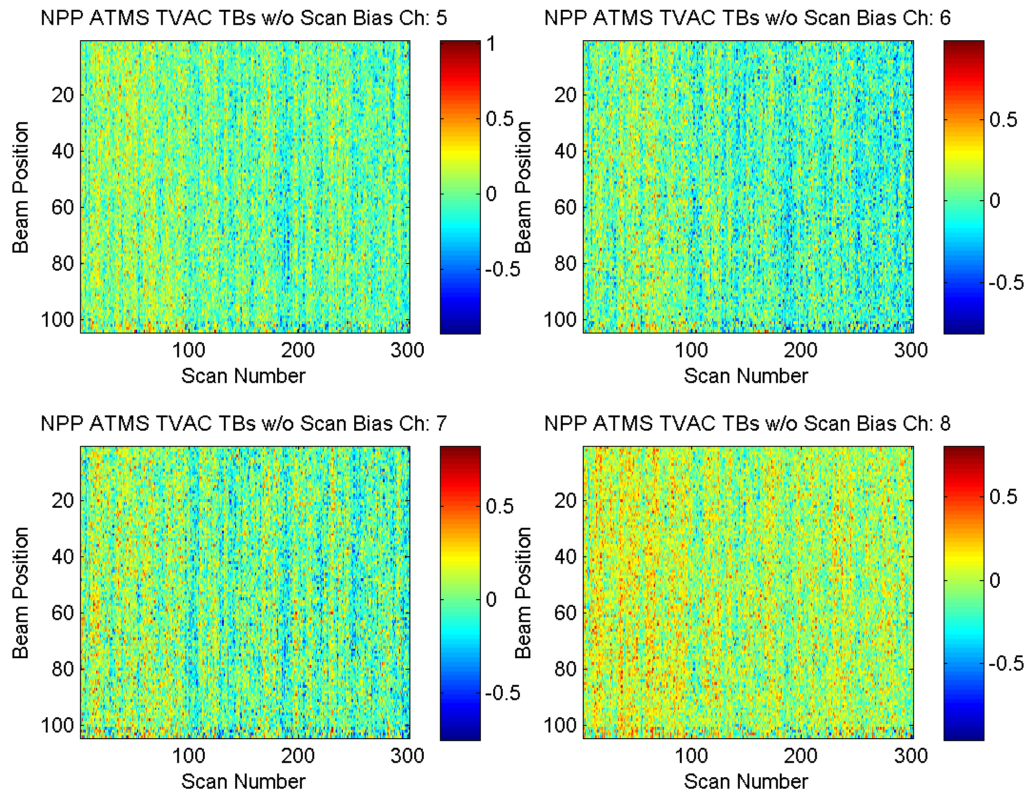
Correlated Observation Error and the ATMS



Advanced Technology Microwave Sounder (ATMS)

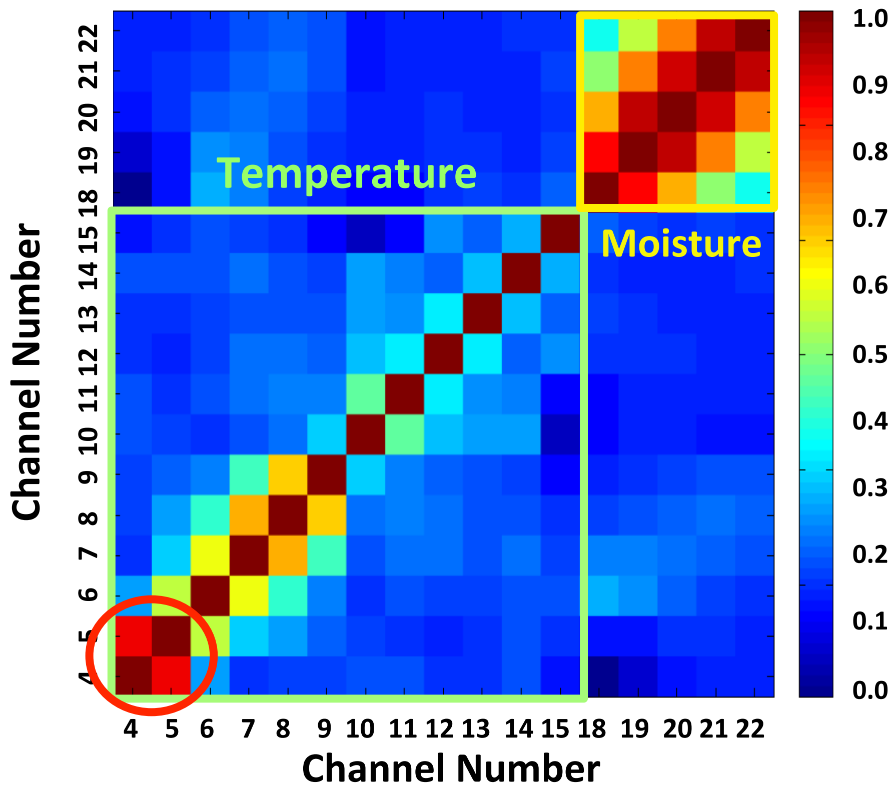
13 temperature channels

9 moisture channels

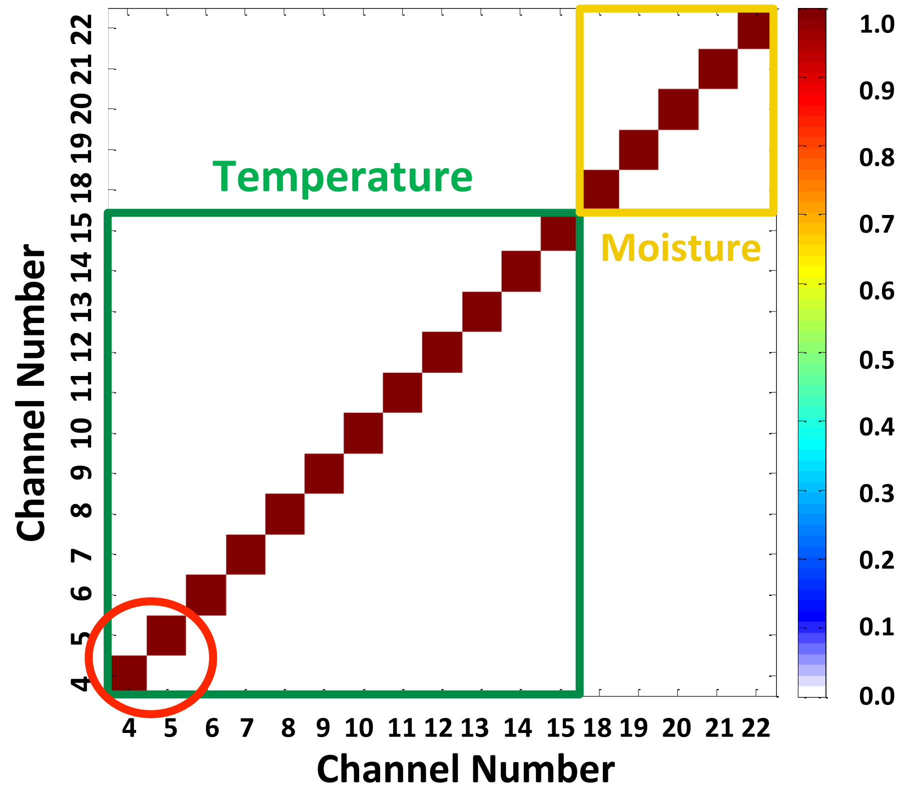


Error Covariance Estimation for the ATMS

Statistical Estimate



Current Treatment



Estimating R is insufficient; we must be able to *use* it to assimilate data with correlated error

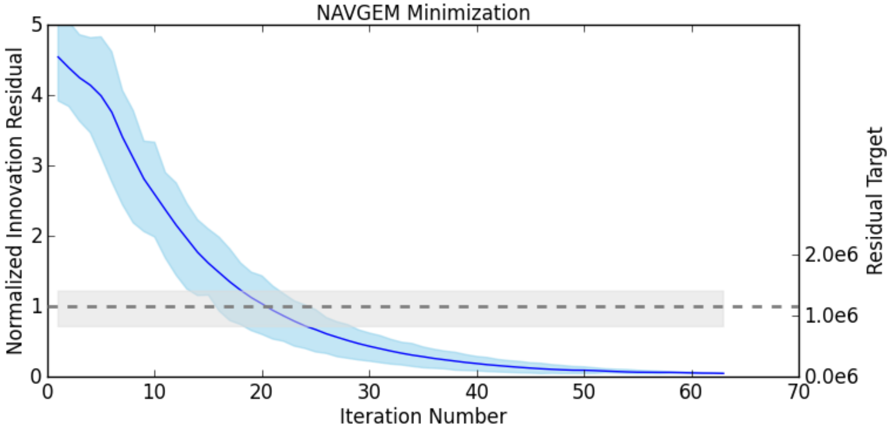
Initial Experiments

- We ran NAVGEM 1.3 at T425L60 resolution with the full suite of operational instruments for two months, from July 1, 2013 through Aug 31, 2013
- The control experiment used a diagonal **R** for the ATMS instrument
- The ATMS experiment used the **R** diagnosed from the Desroziers method applied to three months of innovation statistics
- **R** was symmetrized, but not otherwise altered

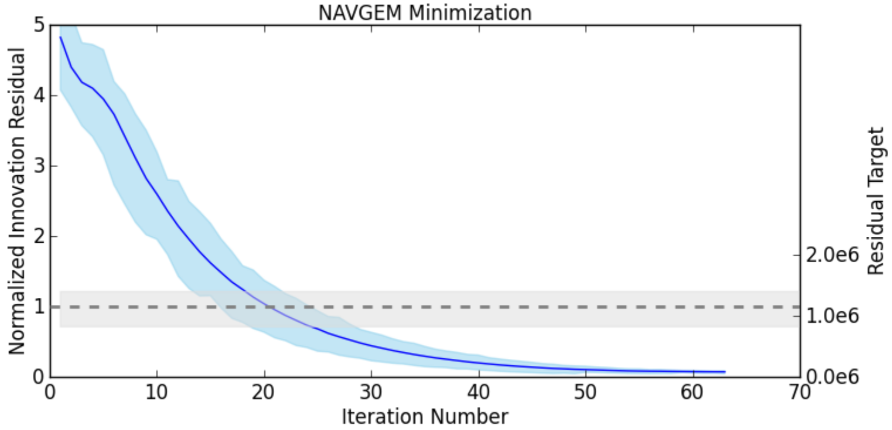
Conjugate Gradient Convergence

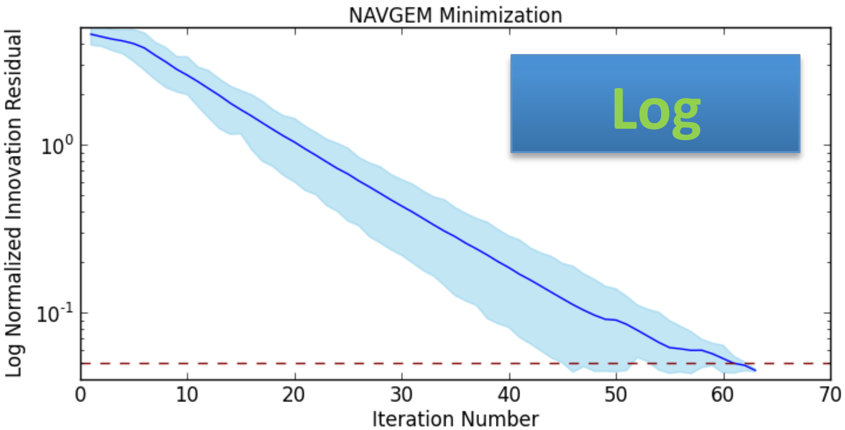
2013080200

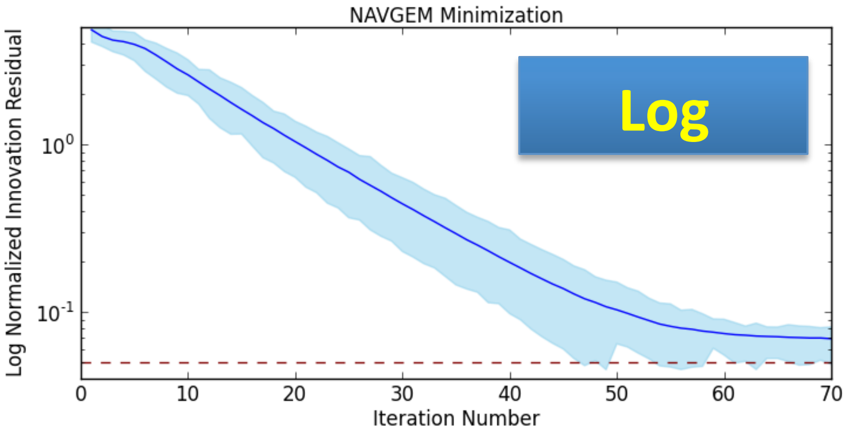
Control



Experiment



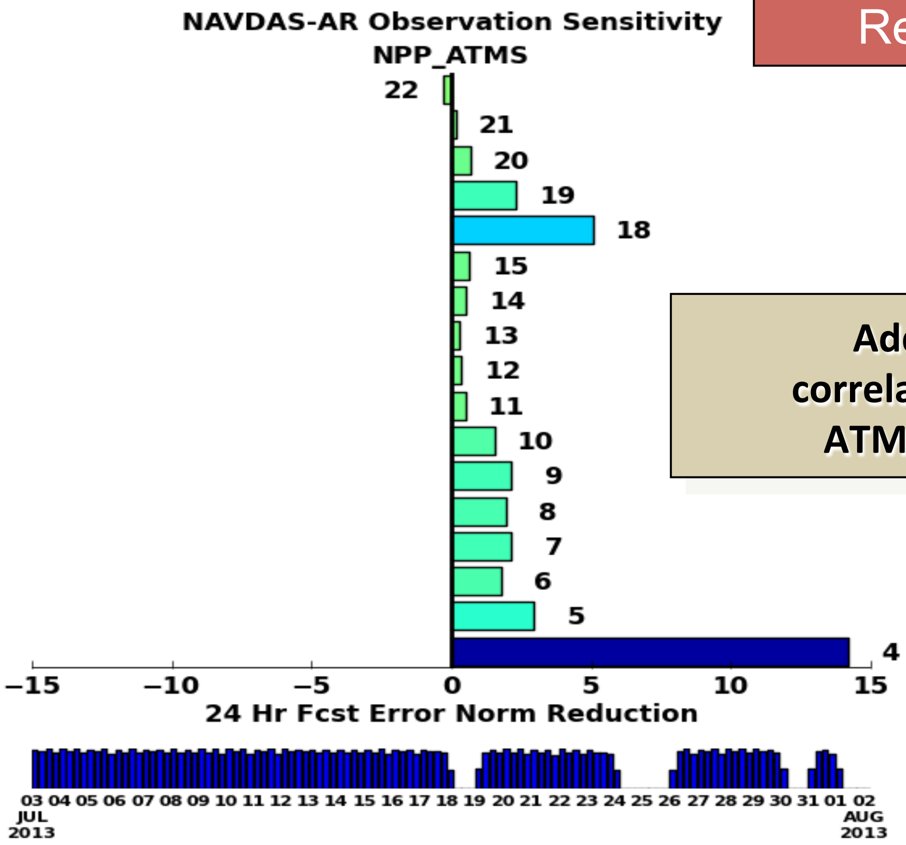




Assess Forecast Impact with Observation Sensitivity Tools

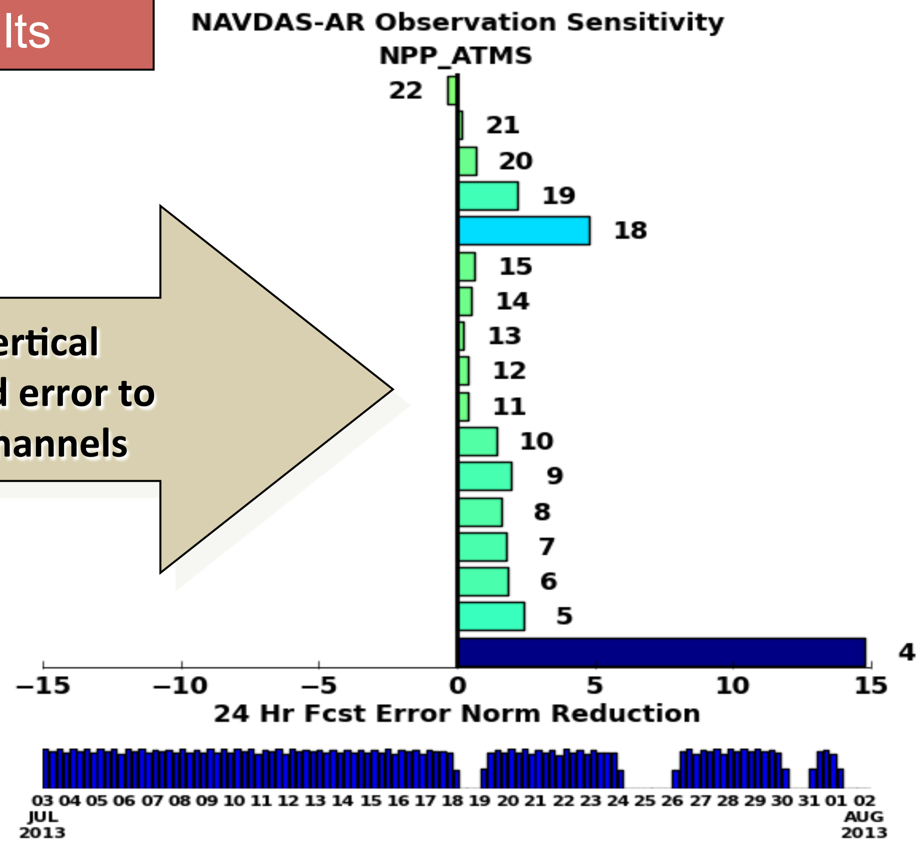
NAVDAS-AR Results

Jul01-Aug02, 2013



Add vertical correlated error to ATMS channels

Jul01-Aug02, 2013



Adjoint-based system (Langland and Baker, 2004) enables rapid assessment of changes to the DA system

Preliminary Results

2013070100-2013083012

Lead Time

0 24 48 72 96 120

atms by Lead Time 2013070100-2013083012

Show All entries

Filter:

Global RMS Temperature Error at 250 hPa vs. Radiosondes

Global RMS Temperature Error at 850 hPa vs. Radiosondes

Tropical RMS Temperature Error at 500 hPa vs. Self-analysis

(NH/SH) RMS Vector Wind Error at 850 hPa vs. Self-analysis

Tropical RMS Vector Wind Error at 850 hPa vs. Self-analysis

NH Geopotential Anomaly Correlation at 1000 hPa vs. Self-analysis

Reference	Level	Metric	Variable	Level type	Region	0	24	48	72	96	120	Mean
Fixed Buoy	None	Mean Error	Wind Speed	surface	Northern Hemisphere							+
Fixed Buoy	None	Mean Error	Wind Speed	surface	Southern Hemisphere							+
Fixed Buoy	None	Mean Error										+
Radiosondes	50.0	RMS Error										+
Radiosondes	250.0	RMS Error										+
Radiosondes	250.0	Vector RMS Error	Wind	pressure	Global							+
Radiosondes	500.0	RMS Error	Geopotential Height	pressure	Global							+
Radiosondes	850.0	RMS Error	Air Temperature	pressure	Global							+
Radiosondes	850.0	Vector RMS Error	Wind	pressure	Global							+
Self Analysis	100.0	RMS Error	Geopotential Height	pressure	Atlantic Region							+
Self Analysis	100.0	RMS Error	Geopotential Height	pressure	Eastern Pacific							+
Self Analysis	100.0	RMS Error										+
Self Analysis	100.0	RMS Error										+
Self Analysis	100.0	RMS Error										+
Self Analysis	100.0	RMS Error	Geopotential Height	pressure	Western Pacific							+
Self Analysis	200.0	RMS Error	Geopotential Height	pressure	Atlantic Region							+
Self Analysis	200.0	RMS Error	Geopotential Height	pressure	Eastern Pacific							+
Self Analysis	200.0	RMS Error	Geopotential Height	pressure	Northern Hemisphere							+
Self Analysis	200.0	RMS Error	Geopotential Height	pressure	Southern Hemisphere							+
Self Analysis	200.0	RMS Error	Air Temperature	pressure	Tropics							+
Self Analysis	200.0	RMS Error	Geopotential Height	pressure	Tropics							+
Self Analysis	200.0	RMS Error	Geopotential Height	pressure	Western Pacific							+
Self Analysis	200.0	Vector RMS Error	Wind	pressure	Northern Hemisphere							+
Self Analysis	200.0	Vector RMS Error	Wind	pressure	Southern Hemisphere							+
Self Analysis	200.0	Vector RMS Error	Wind	pressure	Tropics							+
Self Analysis	500.0	Anomaly Correlation					+					+
Self Analysis	500.0	Anomaly Correlation										+
Self Analysis	500.0	Anomaly Correlation										+
Self Analysis	500.0	Anomaly Correlation										+
Self Analysis	500.0	Anomaly Correlation	Geopotential Height	pressure	Tropics							+
Self Analysis	500.0	Anomaly Correlation	Geopotential Height	pressure	Western Pacific							+
Self Analysis	500.0	RMS Error	Air Temperature	pressure	Tropics							+
Self Analysis	500.0	Vector RMS Error										+
Self Analysis	500.0	Vector RMS Error										+
Self Analysis	500.0	Vector RMS Error										+
Self Analysis	850.0	RMS Error	Air Temperature	pressure	Tropics							+
Self Analysis	850.0	Vector RMS Error	Wind	pressure	Northern Hemisphere							+
Self Analysis	850.0	Vector RMS Error	Wind	pressure	Southern Hemisphere							+
Self Analysis	850.0	Vector RMS Error	Wind	pressure	Tropics							+
Self Analysis	1000.0	Anomaly Correlation										+
Self Analysis	1000.0	Anomaly Correlation										+
Self Analysis	1000.0	Anomaly Correlation										+
Self Analysis	1000.0	Anomaly Correlati										+
Self Analysis	1000.0	Anomaly Correlati										+
Self Analysis	1000.0	Anomaly Correlati										+

Conclusions

- The Hollingsworth-Lonnberg and Desroziers error covariance estimation methods can quantify correlated observation error
- The NAVGEM system allows for direct use of a non-diagonal **R**; implementing vertically correlated error is straightforward.
- Correctly accounting for correlated observation error in data assimilation may yield superior forecast results without a large computational cost

Discussion

- <u>How can we best estimate errors in Desroziers/Hollingsworth- Lönnberg diagnostics?</u>
  - Should we expect agreement between different methods?
  - Will the Desroziers diagnostic converge if both R and B are incorrectly specified?
  - Amount of data required to estimate covariances? Seasonal dependence?
  - Best methods to symmetrize the Desroziers matrix?
- <u>How to gauge improvement?</u>
  - Do we also need to adjust to see overall improvement to the system?
  - How do we maintain the correct ratio for DA?
- <u>What about convergence?</u>
  - Should we do an eigenvalue scaling to improve the condition number?